

CONSTRAINTS ON THE FORMATION OF PSR J0737-3039: THE MOST PROBABLE ISOTROPIC KICK MAGNITUDE

B. WILLEMS AND V. KALOGERA

Northwestern University, Department of Physics and Astronomy, 2145 Sheridan Road, Evanston, IL 60208, USA

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ABSTRACT

A strongly relativistic binary pulsar has been recently discovered with the 64m Parkes telescope (Burgay et al. 2003). Here we use the measured properties of this binary (masses and orbital characteristics as well as age estimates), and we derive the complete set of constraints imposed on the physical properties of the binary pulsar progenitor right before the second supernova explosion. We find that: (i) according to our current understanding of neutron-star formation, the helium-rich progenitor of the second neutron star is most likely overflowing its Roche lobe; (ii) the neutron-star kick magnitude is constrained in the range $60\text{--}1560\text{ km s}^{-1}$, with the most probable value being equal to 150 km s^{-1} . While the first conclusion is in agreement with Dewi & van den Heuvel (2003), our upper limit on the kick magnitude is significantly larger than that derived by these authors. We find that the difference arises because Dewi & van den Heuvel (2003) inadvertently neglected to consider kicks directed out of the pre-supernova orbital plane.

Subject headings: Stars: Binaries: Close, Stars: Pulsars: General, Stars: Neutron

1. INTRODUCTION

The significance for relativistic astrophysics of close binaries with two neutron stars, one of which is detected as a recycled pulsar, has been recognized for many years, since the discovery of the first such system (Hulse & Taylor 1975). More than 10 years since the discovery of the second relativistic double neutron star (DNS) PSR B1534+12 (Wolszczan 1991), the discovery of the third system in the disk has been recently announced with important implications for the current expectations for the detection of DNS inspiral by ground-based interferometers (Burgay et al. 2003; Kalogera et al. 2003). This new system has broken a number of barriers already: it harbors the *fastest* PSR (spin period of 22 ms) in all DNS, in the *tightest* orbit (orbital period of 2.4 hr) with the *smallest* eccentricity (0.09) of all DNS. In addition, Lyne et al. (2004) recently reported the discovery of a 2.8 s pulsar companion to the millisecond pulsar, making this the first observed *double pulsar* system.

A number of earlier studies of DNS binaries (e.g. Fryer & Kalogera 1997, and references therein) have examined the evolutionary history of the previously known systems and have derived some constraints related to the formation of the second neutron stars in the binaries. In this *Letter* we consider the recent evolutionary history of PSR J0737-3039 and derive a set of necessary constraints on the supernova kick imparted to the second neutron star (NS) and on its progenitor characteristics. We compare our results to those obtained very recently by Dewi & van den Heuvel (2003, hereafter DvdH) and we comment on the origin of their derived constraints.

2. ORBITAL EVOLUTION AND DYNAMICS

The orbital characteristics of the observed DNS systems are primarily determined by the effects of the supernova explosion (SN) leading to the birth of the second NS and by the subsequent loss of orbital energy and

angular momentum via gravitational radiation. In the case of a symmetric SN explosion, the semi-major axis and eccentricity of the post-SN orbit are uniquely determined by the amount of *mass lost* from the system during the explosion. If, on the other hand, the SN explosion is asymmetric as currently thought, the post-SN orbital parameters also depend on the *magnitude and direction* of the kick imparted to the NS.

In agreement with the current understanding of DNS binaries (Tauris & van den Heuvel 2004) and as we will show in what follows, the tight orbit essentially constrains the pre-SN orbital separation to such small values that the binary just before the explosion is expected to consist of a helium star (the progenitor of the second NS) and the first NS. This pre-SN orbit is expected to be circular due to Roche-lobe overflow (RLOF) from the helium-star progenitor during earlier evolutionary phases. We constrain the mass M_0 of the helium star, the pre-SN orbital separation A_0 , and the magnitude V_k of the kick velocity by considering (i) the orbital evolution of the DNS due to gravitational radiation, and (ii) the orbital dynamics of asymmetric SN explosions (see also Fryer & Kalogera 1997; DvdH).

We first determine the post-SN semi-major axis A and orbital eccentricity e from the currently observed values A_{cur} and e_{cur} by integrating the equations derived by Junker & Schäfer (1992) for the evolution of the orbit due to gravitational radiation backwards in time. To this end, we use the values $A_{\text{cur}} = 1.26 R_\odot$ and $e_{\text{cur}} = 0.0878$ reported by Burgay et al. (2003). For the masses of the pulsar and its companion, we use the values $M_p = 1.34 M_\odot$ and $M_c = 1.25 M_\odot$ expected for an edge-on orbit (see Burgay et al. 2003). Since the characteristic age is derived under the assumption of a birth spin period much smaller than the current spin period, it may be quite unreliable as an estimate for the true age of a recycled pulsar. The characteristic age derived for the second (not recycled) pulsar in PSR J0737-3039 is equally uncertain because the spin evolution of the second-born NS is

likely to be affected by torques exerted by its millisecond pulsar companion (Lyne et al. 2004). We therefore assume that the first-born NS was recycled to maximum spin-up for Eddington-limited accretion and use an estimate for the time τ_b since the pulsar left the spin-up line as an *upper limit* to the time T_{SN} elapsed since the last SN explosion (see Arzoumanian et al. 1999 for details). The post-SN orbital parameters at $T_{\text{SN}} = \tau_b = 100$ Myr are calculated to be $A = 1.54$ and $e = 0.12$. We note that the orbital evolution due to gravitational radiation is relatively slow for this system so that the values of A and e are not greatly sensitive to the adopted value of T_{SN} .

Next, we consider the orbital dynamics of asymmetric, instantaneous SN explosions. As in the past we use the conservation laws of orbital energy and angular momentum to relate the pre-SN parameters (A_0, M_0, M_p) and the kick velocity \vec{V}_k to the post-SN parameters (A, e, M_c, M_p):

$$V_k^2 + V_r^2 + 2 V_k V_r \cos \theta = G (M_p + M_c) \left(\frac{2}{A_0} - \frac{1}{A} \right), \quad (1)$$

$$A_0^2 [V_k^2 \sin^2 \theta \cos^2 \phi + (V_k \cos \theta + V_r)^2] = G (M_p + M_c) A (1 - e^2), \quad (2)$$

where G is the gravitational constant, and $V_r = [G(M_p + M_0)/A_0]^{1/2}$ is the relative orbital velocity of the helium star just before its SN explosion (e.g., Hills 1983; Kalogera 1996). The angles θ and ϕ describe the direction of the kick velocity: $\theta \in [0, \pi]$ is the polar angle between the kick velocity and the relative orbital velocity of the helium star just before the SN explosion, and $\phi \in [0, 2\pi]$ is the corresponding azimuthal angle defined so that $\phi = 0$ represents a plane perpendicular to the line connecting the centers of mass of the binary components (see Kalogera 2000 for a graphic representation).

The requirements that the post-SN orbit must pass through the position of the two stars at the time of the explosion and that $\cos^2 \phi \leq 1$, limit the pre-SN orbital separation to the range $A(1 - e) \leq A_0 \leq A(1 + e)$ (Flannery & van den Heuvel 1975). The range is independent of the helium star mass and the magnitude of the NS kick, and is shown by the grey-shaded region in Fig. 1.

From Eqs. (1) and (2) it is clear that, for a given pair of (M_0, A_0) there is *no unique solution* for the kick magnitude V_k consistent with the post-SN properties (cf. DvdH). Instead Fryer & Kalogera (1997) have shown that the absolute requirement $\cos^2 \phi \geq 0$ yields an upper limit for the mass M_0 of the helium star, for every pair of (A_0, V_k) values:

$$M_0 \leq -M_p + k^2 (M_p + M_c) (A_0/A) \times \left\{ -2 (A/A_0) (1 - e^2)^{1/2} \left[(A/A_0)^2 (1 - e^2) - k \right]^{1/2} + 2 (A/A_0)^2 (1 - e^2) - k \right\}^{-1}, \quad (3)$$

where

$$k = 2 \frac{A}{A_0} - \left[\frac{V_k^2 A}{G (M_p + M_c)} + 1 \right]. \quad (4)$$

The equality in Eq. (3) is valid *only* if the kick is assumed to be restricted in the plane of the pre-SN orbit ($\cos^2 \phi = 0$), and it is only then that the value of V_k can be viewed as an exact solution. For this reason, no strict upper limit on the magnitude of the kick velocity results from Eq. (3), which is in contrast to the conclusion obtained by DvdH. As can be seen from the dotted lines in Fig. 1, the upper limit on M_0 increases with increasing values of V_k .

For a given helium star mass M_0 , the maximum stellar radius reached by the second-born NS's direct progenitor sets an additional divide separating detached from Roche-lobe-filling systems in the (A_0, M_0) parameter space. The divide is represented by the thick dashed line in the left-hand panel of Fig. 1. It follows that in order for the progenitor of PSR J0737-3039 to be detached just before the helium star's SN explosion, the helium star must be more massive than $\simeq 25 M_\odot$ and the kick magnitude must be in excess of $\simeq 1200 \text{ km s}^{-1}$. Although such high kick magnitudes have been discussed in the past (e.g., the guitar nebula - Cordes et al. 1993), helium stars of such high mass are not very likely at the time of the SN explosion, given the strong wind mass loss associated with them (Woosley et al. 1995). In addition, such high-mass helium stars are expected to end up as a black hole instead of a NS (e.g., Fryer & Kalogera 2001; Tauris & van den Heuvel 2004). Nevertheless, none of the above are strict constraints, and therefore we conclude that, although helium stars more massive than $\simeq 25 M_\odot$ cannot be excluded, they are most probably highly unlikely. Hence it appears more reasonable to consider that the helium-star progenitor of the last-born NS was filling its Roche lobe and was transferring mass onto the first-born NS at the time of its SN explosion, in agreement with DvdH.

The fate of NS and helium star binaries undergoing mass transfer from the helium star depends on the orbital period and the mass of the donor star at the *onset of the mass transfer phase*. Since our analysis yields orbital periods and helium star masses *just before the helium star's SN explosion*, the derivation of exact constraints in principle requires detailed mass transfer calculations to map the pre-SN parameter space to the viable parameter space at the onset of RLOF. However, the details of mass-transfer sequences and the exact mapping mentioned above depends on the assumptions in the stellar evolution code adopted (see comparison of results from three studies of this topic: Dewi & Pols 2003, Ivanova et al. 2003, and Dewi et al. 2002). Instead we can use the qualitative effect of such a mass transfer phase to derive robust constraints on the NS progenitor properties. In agreement with other studies Ivanova et al. (2003) found that mass transfer from a helium star that is more massive than the NS companion by a factor greater than 3.5 leads to a delayed dynamical instability which prevents the formation of a DNS. Since the pre-SN helium-star mass is bound to be slightly smaller than the mass at the onset of RLOF, the condition $M_0/M_p \leq 3.5$ leads to a rather conservative upper limit of $4.7 M_\odot$ for the mass of the helium star that formed the companion to PSR J0737-3039. This upper limit is represented by a dashed horizontal line in Fig. 1.

A lower limit on the mass M_0 of the helium star arises from the requirement that the helium star must be mas-

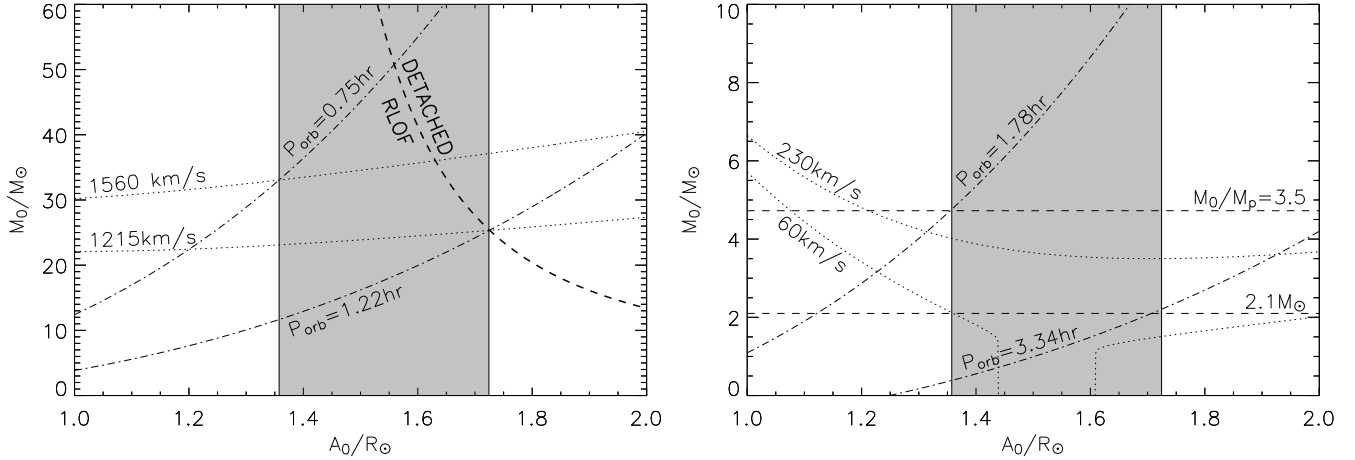


FIG. 1.— Limits on the pre-SN orbital separation A_0 and the helium star mass M_0 for PSR J0737-3039 under the assumption that the last-formed NS was born 100 Myr ago. The grey-shaded vertical region represents the band $A(1 - e) \leq A_0 \leq A(1 + e)$; the thick dashed line separates detached from Roche-lobe overflowing systems; the dotted lines correspond to upper limits on the mass of the helium star for different kick velocity magnitudes; and the dashed horizontal lines indicate the mass limits related to the stability of RLOF and the minimum helium star mass required for the formation of a NS. The dash-dotted curves represent lines of constant orbital period P_{orb} . In the right-hand panel, we zoom in on the parameter space where the helium star is overflowing its Roche lobe.

sive enough to evolve into a NS instead of a white dwarf. However, the value of this lower limit depends on the modelling of massive stars as well as on whether or not the star is affected by binary evolution processes. Current models of helium star evolution indicate that the minimum mass required to form a NS ranges from 2.1 to $2.8 M_\odot$ (Habets 1985, Tauris & van den Heuvel 2004). Here we adopt a conservative value of $2.1 M_\odot$. From Fig. 1, it can be seen that the lower limit on M_0 imposes a lower limit of 60 km s^{-1} on the magnitude of the kick velocity imparted to the second NS. Any higher value for the minimum progenitor mass M_0 shifts the minimum kick velocity to higher values (as it is evident from Fig. 1). In particular, if the lower limit on M_0 would increase to $2.3 M_\odot$ as in DvdH, the minimum required kick velocity is 78 km s^{-1} . The small difference with the lower limit of 70 km s^{-1} obtained by DvdH is due to the different age (and thus different post-SN orbital parameters) adopted by these authors.

Finally, an upper limit on the magnitude of the kick velocity imparted to the last-born NS may be derived from the condition that the binary must remain bound after the SN explosion. The upper limit depends on the pre-SN helium star mass and orbital separation range, and is given by $V_k/V_r = 1 + \sqrt{2(M_p + M_c)/(M_p + M_0)}$ (e.g. Brandt & Podsiadlowski 1995, Kalogera & Lorimer 2000). For the mass and orbital separation constraints ($2.1 \leq M_0/M_\odot \leq 4.7$ and $1.36 \leq A_0/R_\odot \leq 1.72$) derived above, the largest possible kick velocity is $\simeq 1560 \text{ km s}^{-1}$.

3. KICK VELOCITY DISTRIBUTIONS

For a given kick magnitude V_k and a given set of post-SN orbital parameters (A, e), Eqs. (1) and (2) form a set of two algebraic equations relating the pre-SN orbital separation A_0 and the NS progenitor mass M_0 to the polar angle θ and the azimuthal angle ϕ that define the kick direction with respect to the helium star's pre-SN orbital velocity. Here we use the constraints on A_0 and M_0 to derive constraints on the kick direction that must be satisfied for a given V_k value. It follows that for kick

velocities between 60 and 1560 km s^{-1} , the polar angle θ is restricted to the range $113^\circ \leq \theta \leq 180^\circ$, so that the kick is generally directed opposite to the orbital motion.

We point out that, assuming an isotropic kick distribution, the constraints on θ and ϕ can be used to derive the likelihood of the kick magnitude V_k : the more restricted the kick direction is, for a given V_k value, the lower the likelihood is. Formally this kick-magnitude likelihood $\Lambda(V_k)$ is obtained by:

$$\Lambda(V_k) = \frac{1}{4\pi} \int_{\theta_1}^{\theta_2} \sin \theta d\theta \int_{\phi_1}^{\phi_2} d\phi, \quad (5)$$

where the boundaries $\theta_1, \theta_2, \phi_1, \phi_2$ of the admissible region are functions of the kick velocity magnitude V_k , and the boundaries ϕ_1 and ϕ_2 are usually also functions of the polar angle θ . Under the assumption that the kick-velocity magnitude is independent of the direction of the kick, the probability $P(V_k)$ that the second-born NS received a kick of magnitude V_k is then obtained by normalising the likelihood so that the integral over all allowed kick velocities is equal to unity.

The probability distribution function $P(V_k)$ for PSR J0737-3039 is plotted in Fig. 2 (thick solid line). The curve has a clear maximum at $\simeq 150 \text{ km s}^{-1}$ which represents the most probable kick magnitude imparted to the pulsar companion at birth. In order to assess the sensitivity of the distribution to our helium-star mass constraints, we also show curves corresponding to different lower and upper limits on the mass of the helium star progenitor of the second-born NS. As can be seen from the figure, the distribution is not very sensitive to changes in the upper limit on the allowed helium star mass range. In the particular case of a slightly higher lower limit of $2.3 M_\odot$ on the mass of the helium star, the peak in the distribution shifts to $\simeq 165 \text{ km s}^{-1}$. For comparison, the kick-velocity distribution for PSR 1534+12 is also shown in Fig. 2.

4. DISCUSSION

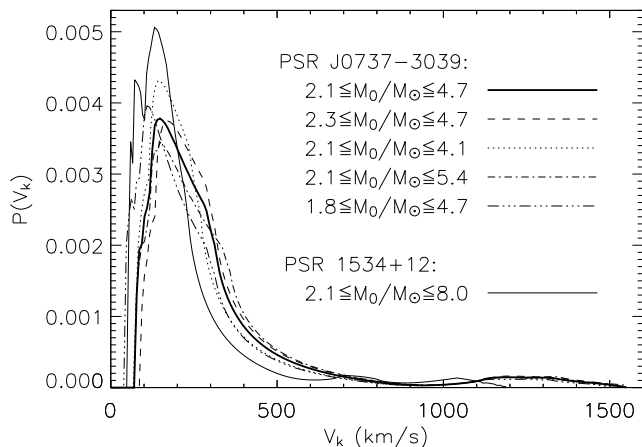


FIG. 2.— Probability distribution function of kick-velocity magnitudes V_k yielding viable progenitors for PSR J0737-3039 for different mass ranges of the second-born NS's progenitor. The non-zero probabilities for kick velocities larger than $\approx 1000 \text{ km s}^{-1}$ correspond to kicks for which the majority of the admissible solutions for θ and ϕ are directed opposite to the pre-SN orbital velocity and perpendicular to the line connecting the components' centers of mass. For comparison, the kick-velocity distribution for PSR 1534+12 is also shown. The mass range for the latter is $2.1 \leq M_0/M_\odot \leq 8.0$.

We derived constraints on the pre-SN progenitor of the newly discovered relativistic binary pulsar PSR J0737-3039. For an assumed age of 100 Myr, the tight limits on the pre-SN orbital separation ($1.36 \leq A_0/R_\odot \leq 1.72$) imply that the progenitor consists of the first-formed NS in orbit around a helium star (and not its hydrogen-rich progenitor since the system would then be in a common-envelope phase with a spiral-in time scale that is much shorter than the evolutionary time scale leading to the SN explosion). We found that the helium star is most likely overflowing its Roche lobe and constrained its mass to be between $2.1 M_\odot$ and $4.7 M_\odot$. The lower limit of $2.1 M_\odot$ implies that a birth kick with a velocity of at least 60 km s^{-1} was imparted to the second-born NS, in agreement with the minimum kick velocity derived by DvdH. From the condition that the binary must remain bound after the second SN explosion, we derived an upper limit for the kick velocity of 1560 km s^{-1} . This is in contrast to the upper limit of 230 km s^{-1} derived by DvdH, which is valid only if the kick is restricted to the pre-SN orbital plane. These results are fairly insensitive to the adopted

age: if the system were only 50 Myr old, the progenitor and kick constraints are $1.27 R_\odot \leq A_0 \leq 1.57 R_\odot$ and $65 \text{ km s}^{-1} \leq V_k \leq 1610 \text{ km s}^{-1}$. The allowed helium star mass range is independent of the adopted age.

We furthermore extended the constraints on NS formation and, for the first time, derived a probability distribution for the kick magnitude imparted to the second-born NS in a DNS binary (PSR J0737-3039). The distribution exhibits a clear maximum at 150 km s^{-1} which is fairly independent of the allowed helium star mass range and the assumed age of the system. In addition, a small secondary peak was found for kick velocities larger than $\approx 1000 \text{ km s}^{-1}$ which mainly correspond to kicks directed opposite to the pre-SN orbital velocity and perpendicular to the line connecting the components' centers of mass.

We also applied the analysis described above to the other two relativistic DNS systems known in the galactic disk. These systems may arise from detached as well as semi-detached pre-SN progenitors. An upper limit for the mass of the helium star in these progenitors is therefore given by the largest possible helium star mass forming a NS instead of a black hole. If we set this upper limit at $8 M_\odot$, the most likely kick velocity imparted to the second-born NS in PSR 1913+16 is 240 km s^{-1} . In addition, it turns out that kicks smaller than 170 km s^{-1} are allowed but have a vanishingly small probability. This is in contrast to the findings of Fryer & Kalogera (1997) and Dewi & Pols (2003) who found minimum kick velocities of 260 km s^{-1} and 70 km s^{-1} , respectively. Note, however, that in the derivation of the kick-velocity distribution for PSR 1913+16 we did not yet take into account the measured space velocity as was done by Wex et al. (2000). We will include this in a forthcoming investigation on the spin-orbit misalignment of PSR J0737-3039A, where we will also present a more detailed comparison between the possible kick velocities and kick directions imparted to the last-born NS in PSR 1913+16 and PSR J0737-3039. Finally, for PSR 1534+12, we find that the most likely kick velocity imparted to the second-born NS is 130 km s^{-1} and that kick velocities below 100 km s^{-1} have a vanishingly small probability.

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